The Atmospheric Vortex Engine.

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***Abstract* - Mechanical energy is produced when heat is carried upward by convection in the atmosphere. An atmospheric vortex engine (AVE) uses an artificially created anchored tornado like vortex to capture the mechanical energy produced during upward heat convection. The vortex is created by admitting warm or humid air tangentially into the base of a circular wall. The heat source can be solar energy, warm sea water, warm humid air or waste industrial heat. There is no need for solar collectors; the heat collector is the earth's surface in its natural state. The AVE has the same thermodynamic basis as the solar chimney except that the physical chimney is replaced by centrifugal force in a vortex and that the solar collector is replaced by the earth's surface in its unaltered state. The mechanical energy is produced in peripheral turbo-generators.**

The AVE has a large energy production potential and could alleviate global warming by reducing the quantity of fuel required to meet energy needs. An AVE would increase the efficiency of a thermal power plant by reducing its cold source temperature from the temperature at the bottom of the troposphere to the temperature of the tropopause. The AVE process could remediate global warming by lifting heat above greenhouse gases so that the heat can be more easily radiated to space.

Keywords: Convection; vortex; atmosphere; engine; solar; energy; tornado; water; global warming.

I. INTRODUCTION

The AVE harnesses the energy responsible for hurricanes, tornadoes and waterspouts [1-6]. The mechanical energy produced during upward heat convection is equal to upward heat flow multiplied by the Carnot efficiency based on the average temperatures at which the heat is received and given up [1-4]. The work of convection is calculated by applying the total energy equation to an open steady-state ideal thermodynamic system. The work produced in a specific adiabatic reversible cycle is important because it is the maximum work that can be produced in an adiabatic re-arrangement process. Once ideal cycles are understood, irreversible cycles can readily be explained. The author previously showed that the maximum potential intensity of hurricanes can be calculated by applying the total energy equation [7] to a process wherein the raised air approaches equilibrium with the underlying surface at reduced surface pressure.

The AVE proposal was initially presented by the author in the Bulletin of the American Meteorological Society in 1975 [8] and expanded upon in 1999 in the Journal of Applied Energy [9].

The AVE has the same thermodynamic basis as the solar chimney [10] except that the wall of the physical chimney is replaced by centrifugal force in a vortex and that the solar collector is replaced by the earth's surface in its unaltered state. A solar chimney consists of a tall vertical tube surrounded by a transparent solar collector with a turbine located in the base of the tube. The Manzanares solar chimney built in Spain in the 1980`s operated for 7 years and had an electrical output of 50 kW. The solar chimney was 200 m tall and 10 m in diameter and was surrounded by a solar collector 250 m in diameter.

II. VORTEX ENGINE DESCRIPTION

Fig. 1 and 2 shows elevation and plan views of a vortex engine. The heat required to sustain the vortex can be the naturally occurring heat content of ambient air or can be provided in peripheral heat exchangers; the heat source for the heater can be warm seawater or waste industrial heat. The air heaters can be wet or dry heat exchangers. The mechanical energy is produced in peripheral turbo-generators. The circular wall could have a diameter of 200 m and a height of 100 m; the vortex could have a diameter of 30 m at its base and could extend to a height of up to 15 km. The system could generate 200 MW of electrical power. A vortex engine could look like an open roof circular arena or a natural draft cooling tower with a small tornado firmly anchored at its centre.

Admitting warm air tangentially into the base of a vertical axis cylindrical wall produces a convective vortex which acts as a dynamic chimney. The vortex would be started by temporarily heating the air near the centre of the station with fuel or steam. The starting steam could be injected in the tangential entries to help entrain the air in the station while at the same time heating the air. The pressure difference between the ambient air surrounding the station and the base of the vortex drives the turbines.

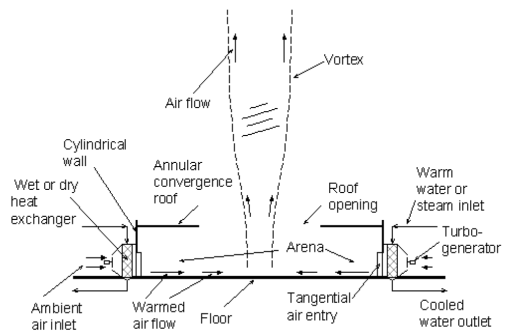

Figure 1. Atmospheric Vortex Engine – side view

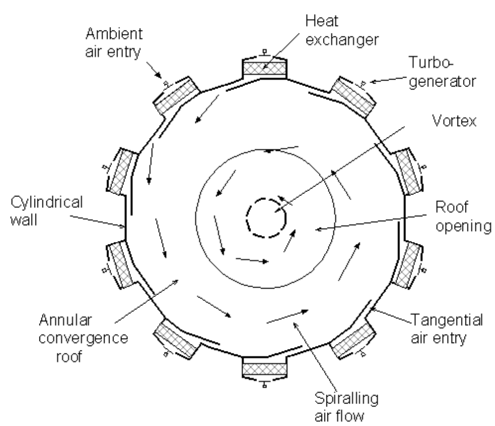

Figure 2. Atmospheric vortex Engine – plan view

Warm air enters the area within the cylindrical wall, called the arena, via tangentially oriented ducts. The airflow is controlled with adjustable restrictors located either upstream of the air heaters or within the tangential entry ducts. An annular roof with a central circular opening forces the air entering the arena to converge thereby forming a vortex with a diameter somewhat smaller than the diameter of the roof opening. The vortex is stopped by restricting the flow of heated air.

The concept was tested on 1 m and 4 m diameter physical models. The 4 m diameter model produced a 30 to 50 cm diameter vortex extending up to 20 m above the top of the model. Propane heaters were used to warm the air upstream of the tangential entry ducts. The vortex, which looked like a miniature tornado, was made visible with saltpeter smoke emitters. Model photos and videos are available on the Vortex Engine web site [11].

A natural draft chimney is a cylinder in radial compression which prevents cooler ambient air from mixing with warm rising flue gas. In a vortex, the centrifugal force replaces the physical chimney wall and prevents ambient air from becoming entrained in the rising air stream. The diameter of the vortex is self-regulating and adjusts itself until the radial pressure differential is balanced by centrifugal force. The entry of air in the vortex is restricted to a thin layer next to the underlying surface wherein tangential velocity is reduced by friction. The energy loss due to friction in the upper part of the vortex is small because friction losses in large diameter conduits are small. The kinetic energy of the rising air is recovered when the air decelerates as the vortex diameter expands near the top of the vortex. Between the times when the kinetic energy is produced and recovered, circular motion provides centrifugal force thus creating a virtual dynamic chimney.

Cooling towers are commonly used to transfer waste heat to the atmosphere. Using round numbers for illustration, a 500 MW thermal power plant typically rejects 1,000 MW of waste heat. An atmospheric vortex engine could increase the electrical output of a 500 MW plant to 700 MW by converting 20% of its 1,000 MW of waste heat into work, thereby increasing the output of the power plant by 40%. The AVE increases the efficiency of a thermal power plant by reducing the temperature of the heat sink from +30 °C at the bottom of the atmosphere to – 70 °C at the tropopause.

Wet cooling towers are the preferred type of cooling towers when water is available because there is no need for physical separation of the fluids and because the cooled water temperature can approach the wet bulb temperature of the air. In a wet cooling tower, the water drops on splash bars and is repeatedly broken up into small droplets to enhance contact between air and water. Mechanical draft cooling towers use fans to circulate the air. Natural draft cooling towers use a hyperbolic stack up to 200 m tall to produce a draft. The cost of natural draft cooling tower is two to four times the cost of mechanical draft cooling towers. The higher cost is justified because there is no need for energy to drive fans, which can consume up to 4% of the electricity produced. The hyperbolic stack is an energy producer in the sense that it eliminates the need to power fans. The air leaving a wet cooling tower approaches equilibrium with the water entering the cooling tower. The air leaving a vortex engine using seawater as the heat source could be saturated at a temperature of 1 to 2 °C lower than the sea surface temperature (SST).

III. Thermodynamic Basis

Fig. 3 shows the ideal thermodynamic process of the atmospheric vortex engine. The water spray represents the wet cooling tower wherein enthalpy is transferred from water to air. The total energy equation:

$$w = q - \Delta h - \Delta gz - \Delta \frac{v^2}{2} \qquad (1)$$

is used to calculate the energy received and produced in each of the three processes shown in the figure, where w is work, q is heat, h is the enthalpy of the air including the enthalpy of its water content, g is the acceleration of gravity, z is height, and v is velocity. Entropy (s) is conserved in reversible adiabatic processes 1-2 and 3-4. In the ideal cycle, the velocity of the air at the four numbered states is taken to be negligible. The air approaches equilibrium with the water at reduced pressure at point 3.

The key to solving the problem is realizing that all the work is transferred to the point where the flow is restricted, expansion process 1-2. The work during process 3-4 is zero. The pressure at the base of the vertical tube is calculated by assuming an approach to equilibrium at state 3, calculating the work during process 3-4 for two P_3 guesses, and then interpolating to determine the value of P_3 required the make the work w_{34} zero. Point 4 is at the level of neutral buoyancy. A second iteration is required to find the value of P_4 that maximizes w_{12}.

Table 1 shows a sample process calculation. State 3 air conditions correspond to the condition at hurricane eyewall. State 1 temperature was selected so that the work is zero without heat addition. The water temperature could be 26°C. The pressure at the base of the vertical tube calculated by the above iteration method is 97.7 kPa. The heat received during process 2-3 is 8490 J kg^{-1}. The specific work is 2984 J kg^{-1}. The efficiency (n) is 35%. The specific work of 2984 J kg^{-1} corresponds to a velocity of 77 m/s. Recent high precision dropwindsonde measurements in hurricane Isabel showed eyewall wall sea surface temperature of 26 °C, eyewall surface air temperature of 24.5 °C, and maximum wind velocity of 77 m/s.

The efficiency (n) corresponds to the Carnot efficiency given by: $n = 1 - T_4 / T_3$, where T_3 and T_4 are the temperatures at the bottom and at the top of the vertical tube in degrees Kelvin, the temperatures at which heat is received and given up. Approximately 35% of the heat received is converted to work during the convection process irrespective of whether the heat is received as sensible or latent heat. Saturating the air with 30 °C water would yield a specific work of 25000 J kg^{-1} corresponding to a velocity of 220 m/s. A power output of 200 MW could result from an air flow of 20 Mg/s and a specific work of 10 kJ kg^{-1}. The minimum SST required for hurricane is 26 °C. Tropical sea surface temperatures can be as high as 32 °C. The temperature of power plant waste heat can be as high as 50 °C.

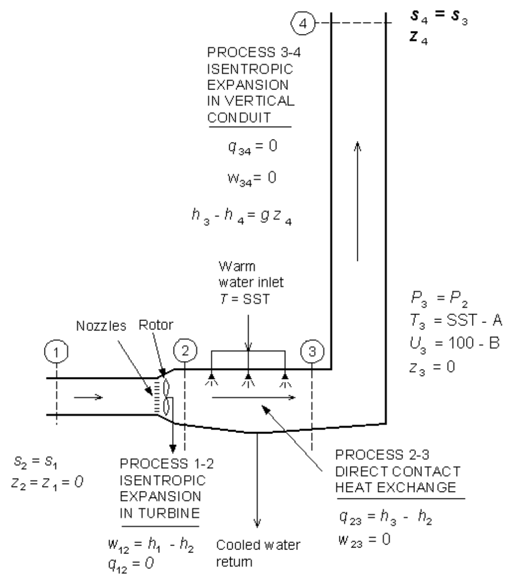

Figure 3. AVE ideal thermodynamic process

IV. Discussion

Reduced pressure enhances the heat transfer from water to air thereby increasing the enthalpy of the air. For the same temperature air at low pressure can hold more moisture than air at higher pressure. The saturation mixing ratio for air at 25 °C is 20.3 g kg^{-1} at 100 kPa and 21.4 g kg^{-1} at 95 kPa. The height of the 10 kPa surface is fairly constant in low latitudes and can be 1,000 m lower in winter middle latitudes than in the tropics. Therefore for a given water temperature, the work could be 10 kJ kg^{-1} higher in middle latitudes winter than in tropical latitudes. For a given water temperature, the work calculated using height based on a tropical sounding is therefore a minimum. The density of the air inside the tube is lower than the density of ambient air at the same level partly due to the temperature of the rising air being higher than that of the ambient air, and partly due to the pressure in the tube being lower than the ambient pressure.

TABLE I. SAMPLE ENERGY CALCULATIONS

(a) Process Conditions

Parameter	P	T	U	r
State	*kPa*	*°C*	*%*	*$g \cdot kg^{-1}$*
1	101.1	25.8	80	16.9
2	97.7	22.9	92	16.9
3	97.7	24.5	97	19.6
4	10.0	-80.9	n/a	19.6

(b) Thermodynamic Properties

Parameter	s	h
State	*$J \cdot (kg \cdot K)^{-1}$*	*$J \cdot kg^{-1}$*
1	241.0	68928
2	241.0	65943
3	269.7	74433
4	269.7	-91130

(c) Energy

Parameter	Equation	Value	Unit
q_{23}	$h_3 - h_2$	8490	$J \cdot kg^{-1}$
w_{12}	$h_1 - h_2$	2985	$J \cdot kg^{-1}$
n	w_{12} / q_{23}	35	%
n	$1 - T_4/T_3$	35	%
v_2	$(2 \cdot w_{12})^{0.5}$	77.2	$m \cdot s^{-1}$
z_4	n/a	16570	m

The water temperature could be 26°C.

The temperature of saturated air decreases less rapidly with decreasing pressure than the temperature of unsaturated air because the heat of condensation warms the rising air. Heat of condensation comes into play once the condensation level has been reached which is usually at elevations of between 500 and 3,000 m. The heat source in a conventional solar chimney, which cannot be high enough to reach the level of condensation, must be sensible heat. The heat source in a vortex engine, where the vortex can extend well past the condensation level, can be the latent heat or sensible heat.

The heat source in an atmospheric vortex engine can have a lower temperature than the heat source in a conventional solar chimney because evaporation can occur at wet bulb temperature which is lower than dry bulb temperature. Producing 3000 J kg^{-1} of work would require a heat source temperature of 24.5°C when the heat source is water, 33°C when dry heat is supplied downstream of the turbine, and 36°C when dry heat is supplied upstream of the turbine.

Tropical cyclones depend on self-induced heat transfer from the oceans [2, 12, 13]. The energy of hurricanes is mainly due to the enhanced sea to air heat transfer as a result of spraying water into the air [12]. Evaporatively cooled spray falling back in the sea reduces SST and the reduced SST tends to reduce the intensity of the hurricane. The passage of a hurricane can reduce sea surface temperature by 3 to 6 °C [2, 13].

Giving the rising air rotation about the vertical axis causes the air to spin as it rises. The resulting centrifugal force opposes the radial differential pressure. Turbulence is inhibited because if a particle of air moves inward its tangential velocity increases to conserve angular momentum, resulting in an increase in centrifugal force which in turn pushes the particle back outward. As a result the flow in the vortex is laminar instead of turbulent, as evidenced by the smooth threads shape occasionally observed in tornadoes and waterspouts. Centrifugal force stabilizes the flow thereby reducing turbulence and friction losses. The rising air behaves like a spinning top being raised; there is little decrease in the angular momentum of the large mass of rising air in the 30 minutes or so required for the air to rise to the top of the troposphere.

Based on a specific work of 10 kJ $kg^{-1}$of air, a 200 MW vortex engine would have a heat input of 1,000 MW with air and water flows of 20 Mg/s, and 40 Mg/s respectively. In a vortex engine with 20 peripheral wet heat exchangers, the work and heat duty per sector could be 10 MW and 50 MW respectively. Each sector would have a single 10 MW turbine, which could have a diameter of 5 m. Based on a precipitation rate of 10 grams of water per kilogram of air, the precipitation would be 0.2 Mg/s or 17,000 Mg/d.

The feasibility of the process could be demonstrated with a 50 m diameter proof of concept pilot plant. A pilot plant would not need heat exchangers if the air were heated with steam and would not need turbines or generators. The elimination of fan power and the reduction in cooled water temperature alone could justify the cost of replacing the cooling tower.

Naturally occurring tornadoes can be dangerous, but the vortex engine would be provided with numerous safety features to eliminate hazards. Redundant air dampers and quench systems could be provided to permit rapid shutdown. In any case the air flow and the diameter of the vortex would be limited by the size of the tangential air entries. Natural vortices are rare in spite of the fact that natural heat sources are abundant. Initial testing could be restricted to remote locations and stable atmospheric conditions until the ability to control the vortex, including starting and stopping at will, is demonstrated. An AVE could reduce the likelihood of natural storms by reducing the heat content of the surface air in its vicinity.

In addition to producing energy, the AVE process could be used to alleviate global warming, to produce precipitation, to enhance the performance of cooling towers, or to clean or elevate polluted surface air. The precipitation produced by an AVE would be small compared to that produced in natural storms. The 20,000 Mg/d of precipitation produced by a 200 MW vortex power station would produce a rainfall of 2 mm/d when spread over an area of 10 km^2. The horizontal extent of the cloud cover in the downwind direction could be 20 km. Airplanes could easily avoid the small highly visible vortex in a known location.

The most favourable sites for the production of controlled vortices are likely to be found in maritime tropical locations. The water production benefits would be very valuable in dry climates. The large difference in temperature between waste heat source and ambient air in cold climates could provide favorable locations when the heat source is waste heat.

The AVE has potential to produce large quantities of energy because the atmosphere is heated from the bottom by solar radiation and cooled from the top by infrared radiation and because there is a potential to convert approximately 15% of the heat carried upward by convection into work. The energy production potential of the AVE is far greater and its cost is far less than those of more conventional solar power plants because the solar collector is the earth's surface in its unaltered state. Providing the energy need of a city with conventional solar power plants would require an area 50 to 500 times the area of the city and would make the area unavailable for other uses such as farming. An AVE power plant would not affect surrounding land use and would have about the same footprint as a thermal power plant of equivalent capacity.

The existence of tornadoes, water-spouts, and dust-devils provides experimental proof that low intensity solar heat can produce high intensity mechanical energy. Developing the atmospheric vortex engine will require determination and cooperation between engineering and atmospheric science disciplines, but the technical challenges would be no more complex than typical industrial processes.

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